SMC-TR-98-22

AEROSPACE REPORT NO.
TR-98(8555)-6

The Effects of Ambient Temperature Fluctuations on the Long-Term Frequency Stability of a Miniature Rubidium Atomic Frequency Standard

15 February 1998

Prepared by

R. P. FRUEHOLZ
Electronics Technology Center
Technology Operations

Prepared for

SPACE AND MISSILE SYSTEMS CENTER
AIR FORCE MATERIEL COMMAND
2430 E. El Segundo Boulevard
Los Angeles Air Force Base, CA 90245

19980722 055

Engineering and Technology Group

THE AEROSPACE CORPORATION
El Segundo, California

This report was submitted by The Aerospace Corporation, El Segundo, CA 90245-4691, under Contract No. F04701-93-C-0094 with the Space and Missile Systems Center, 2430 E. El Segundo Blvd., Suite 6037, Los Angeles AFB, CA 90245-4687. It was reviewed and approved for The Aerospace Corporation by R. P. Frueholz, Principal Director, Electronics Technology Center. Maj. J. W. Cole was the project officer for the Mission-Oriented Investigation and Experimentation Program (MOIE) program.

This report has been reviewed by the Public Affairs Office (PAS) and is releasable to the National Technical Information Service (NTIS). At NTIS, it will be available to the general public, including foreign nationals.

This technical report has been reviewed and is approved for publication. Publication of this report does not constitute Air Force approval of the report's findings or conclusions. It is published only for the exchange and stimulation of ideas.

J. W. Cole, Maj, USAF

J. W. Cole, Maj. USAF
SMC/AXES

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY (*Leave blank*)

2. REPORT DATE
15 February 1998

3. REPORT TYPE AND DATES COVERED

4. TITLE AND SUBTITLE
The Effects of Ambient Temperature Fluctuations on the Long-Term Frequency Stability of a Miniature Rubidium Atomic Frequency Standard

5. FUNDING NUMBERS
F04701-93-C-0094

6. AUTHOR(S)
Frueholz, Robert P.

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
The Aerospace Corporation
Technology Operations
El Segundo, CA 90245-4691

8. PERFORMING ORGANIZATION REPORT NUMBER
TR-98(8555)-6

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Space and Missile Systems Center
Air Force Materiel Command
2430 E. El Segundo Blvd.
Los Angeles Air Force Base, CA 90245

10. SPONSORING/MONITORING AGENCY REPORT NUMBER
SMC-TR-98-22

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited

12b. DISTRIBUTION CODE

13. ABSTRACT (*Maximum 200 words*)

Rubidium (Rb) gas cell frequency standards display a wide range of performance characteristics. At one extreme are relatively large and heavy standards developed for high performance applications such as Global Positioning System (GPS) satellites. At the other extreme are miniature commercial units with sizes and weights less than 10% of the satellite clocks. Military and commercial satellites have growing needs for accurate frequency and time information. A new generation of miniature Rb frequency standards (MRFSs)– or vacuum-optimized variants–is now being produced by a number of different manufacturers. These MRFSs appear attractive for future space applications where size, weight, and power considerations are of extreme importance. Thus far, though, medium- to long-term (frequency averaging times greater that 10^3 s) frequency stabilities of the MRFSs do not match those of the high performance devices. The focus of the current study has been to understand the origins of the frequency noise typically observed in MRFSs over the medium to long term. We have investigated the frequency stability of an MRFS under varying levels of ambient temperature control. We find that a major contributor to long-term frequency noise is ambient temperature fluctuations. Under conditions of tight temperature control, the miniature units tested displayed excellent frequency stabilities, meeting anticipated needs for satellite communication systems. The "off-the-shelf" test unit did not perform well in the vacuum environment. We do not attribute this to its compact size but rather to specifics of its design that were not developed for the vacuum environment. The correlation between the standard's frequency stability and temperature fluctuations suggests that a compensation scheme based upon measurement of the ambient temperature might be useful. Tests performed are consistent with this expectation.

14. SUBJECT TERMS
Atomic clock
Environmental sensitivities
Rubidium atomic frequency standard

15. NUMBER OF PAGES
13

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT
Unclassified

18. SECURITY CLASSIFICATION OF THIS PAGE
Unclassified

19. SECURITY CLASSIFICATION OF ABSTRACT
Unclassified

20. LIMITATION OF ABSTRACT

Preface

The author wishes to thank Dr. J. C. Camparo for many useful discussions throughout the course of these investigations.

Contents

Preface i

1. Introduction 1
2. Experimental Procedures 2
3. Results 3
4. Conclusions 6

References 7

Figures

1. Experimental apparatus described in the text that is used to measure the performance of an MRFS 2
2. Experimental results of the MRFS's performance in terms of the Allan standard deviation, $\sigma_y(\tau)$, vs averaging time, τ 4
3. MRFS frequency stability during a period of extreme temperature stability 4
4. Experimental results of the Rb COTS clock's performance in terms of the Allan standard deviation 5

Table

1. Performance Results for MRFS 3

1. Introduction

Rubidium (Rb) gas cell frequency standards display a wide range of performance characteristics. At one extreme are standards developed for high performance applications, such as Global Positioning System (GPS) satellites. Such standards weigh 12 lb, have volumes of nearly 230 in.^{3}, and display frequency stabilities given by the expression $s_y(t)$ at $3 \times 10^{-12}\, t^{1/2} + 1.5 \times 10^{-14}$ (Refs. 1,2). At the other extreme are miniature commercial standards, some occupying volumes as small as 13 in.^{3}, weighing only 3/4 lb, consuming approximately 8 W under steady state conditions, and costing less than $2000 (Ref. 3). Military and commercial satellites have growing needs for accurate frequency and time information. The new generation of miniature Rb frequency standards (MRFS) now being produced by a number of different manufacturers, or perhaps vacuum-optimized variants, appears attractive for future space applications where size, weight, and power considerations are of extreme importance.* Thus far, though, performances of the MRFSs, in particular, their frequency stabilities, do not match those of the high performance devices. While the white noise portion of the Allan deviation may be similar for averaging times less than ~1000 s, beyond that point, when the devices are operated in a normal laboratory environment, random walk of frequency noise is often observed. From the perspective of many timekeeping applications, this noise is undesirable and could limit device utility. The focus of the current study has been to understand the origins of the random walk of frequency noise. Specifically, is the noise a result of external perturbations, or is it a manifestation of frequency variations originating from within the MRFS, e.g., instabilities in the intensity of the Rb discharge lamp as implemented in the compact design (Ref. 4)? Also, does the compact nature of these standards in any way fundamentally limit their long-term frequency stabilities?

---

*Additional manufacturers of the miniature Rb atomic frequency standard include: Ball Corporation, Efratom Time and Frequency Products (models FRS-C and FRS-N), EG&G Frequency Products (model RFS-10), and TEKELEC NEUCHATEL TIME (model MCFRS-01).

2. Experimental Procedure

To address the issue of random walk of frequency noise, experiments were performed on two Frequency Electronics, Inc. (FEI), FE-5650A Rb atomic frequency standards. These standards are MRFSs with size, weight, and power requirements as called out in the introduction. Since environmental effects are a potential source of long-term frequency instabilities, the MRFSs were operated while attached to a thermal plate in a vacuum chamber during periods of frequency measurement. The experimental apparatus is shown in Figure 1. The standards were not designed for vacuum operation. Therefore, it is not surprising that attempts to operate the MRFSs under vacuum resulted in poorer frequency stabilities and frequency drift rates far poorer than attempts to operate them under ambient atmospheric pressure. Consequently, the MRFSs were operated primarily at atmospheric pressure in the sealed vacuum chamber. The chamber was sealed at the beginning of each frequency measurement period to remove any effects of variations in atmospheric pressure due to weather. The temperature of the thermal plate was continuously monitored during the frequency measurement periods through measurement of the resistance of a precision thermistor. Tests were performed on the MRFSs over 9 months. Allan variances were extracted from frequency data using the method of overlapping samples (Ref. 5). Prior to the Allan variance analysis, a least-squares process was used to remove linear frequency drift. The frequency measurement system employs a Hewlett-Packard (HP) 5061B-004 cesium beam frequency standard as its frequency reference. Consequently, the measured Allan standard deviation white noise behavior is limited to the stability of that standard, which is approximately $8 \times 10^{-12}/t^{1/2}$, with t being the frequency averaging time.

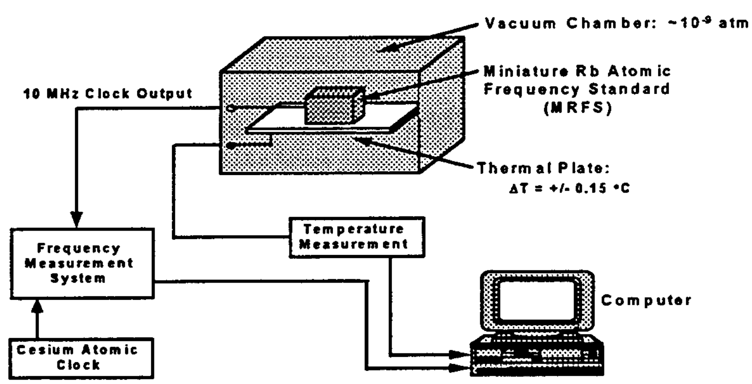

Figure 1. Experimental apparatus described in the text that is used to measure the performance of an MRFS.

3. Results

Over the testing period, the frequency drift rates were seen to monotonically decline. During the first few days of operation after turn-on of the standard, drift rates of approximately 4×10^{-11}/day were observed. After 1 month of operation, a typical frequency drift rate was 7×10^{-12}/day, decreasing to 2×10^{-12}/day after 6 months, and reaching 1×10^{-12}/day after 9 months of operation. Representative sets of Allan variance computations are reported in Figure 2. In this figure, the Allan standard deviation, $\sigma_y(t)$, is plotted as a function of averaging time, t, for the MRFS operating in air. For reference, we show the typical performance required of an atomic frequency standard that is to be used in a communications satellite system (SATCOM). This desired SATCOM performance is indicated by the dashed curve. Squares correspond to the MRFS operating at room temperature, without any active stabilization of the thermal plate in the vacuum chamber. Clearly, under these conditions, the MRFS would not achieve the desired SATCOM performance. However, as indicated by the circles in Figure 2, stabilizing the temperature of the MRFS improves its performance, and would allow the device to just meet the SATCOM specifications.

The measurements clearly show the importance of external temperature fluctuations on the frequency stability of the compact Rb atomic standard. Under tight temperature control, even this inexpensive device can display very good frequency stability for periods of 10^4 s and beyond. Because maintaining stringent temperature control is often not practical, we investigated correcting the recorded output frequency by making use of the measured external temperature. In this investigation, a linear relationship between MRFS frequency and thermal plate temperature was computed for each frequency measurement period, using a least-squares procedure. The frequency data were then corrected for the effects of temperature using the estimated temperature coefficient and the Allan variance computation performed. Interestingly, for the correction to be most effective, an 1800 s lag had to be introduced between the thermal plate temperature and the MRFS frequency. The triangles in the Figure 2 correspond to the expected performance of a "smart" MRFS that is temperature compensated using the foregoing procedure. The inferred smart MRFS performance is quite good, easily exceeding the desired SATCOM frequency stability. Of course, the stability of the temperature coefficient would have to be analyzed to fully validate the concept of a smart MRFS that self-corrects for the effects of ambient temperature.

The role temperature fluctuations play in the long-term frequency stability is further emphasized in Figure 3. On several occasions during the testing period, the ambient laboratory temperature was unusually stable. This stability resulted in the temperature control maintained by the bath being very tight, less than +/-0.04°C. Outstanding Allan variance behavior was observed, approaching 5×10^{-14} at an averaging time of 30,000 s. The results for the MRFSs operating under atmospheric pressure and various levels of temperature control are summarized in Table 1.

Table 1. Performance Results for MRFS. The Allan deviation is given by $\sigma(\tau) = [a^2/\tau + b^2\tau]^{1/2}$.

Temperature Variations (+/-°C)	a*	b	Minimum Observed Value of Allan Deviation
3 (ambient temp. variations)	7.5×10^{-12}	4×10^{-15}	2×10^{-13}
0.15	7.5×10^{-12}	1×10^{-15}	1×10^{-13}
< 0.04	7.5×10^{-12}	3×10^{-16}	5×10^{-14}

*White noise value is limited by the frequency stability of the measurement system frequency reference (HP 5061B-004 cesium beam frequency standard).

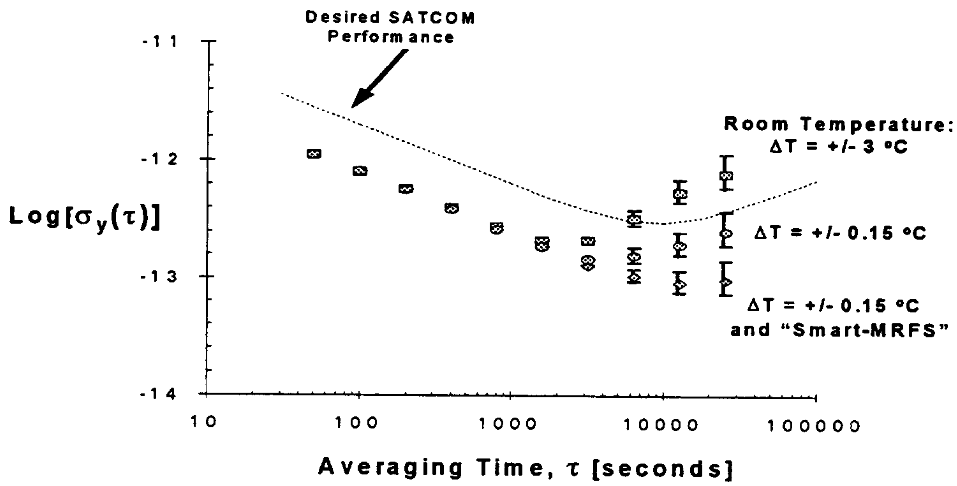

Figure 2. Experimental results of the MRFS's performance in terms of the Allan standard deviation, $\sigma_y(\tau)$, vs averaging time, τ. [The lower the curve of $\sigma_y(\tau)$ vs τ, the better the clock's timekeeping ability.] In the figure, squares represent the MRFS operating in air at room temperature, circles represent the MRFS operating in air with clock temperature stabilized by the thermal plate, triangles represent "smart" MRFS performance in air with clock temperature stabilized by the thermal plate. The dashed line corresponds to frequency stability desired for satellite communications applications, and is only meant for reference purposes.

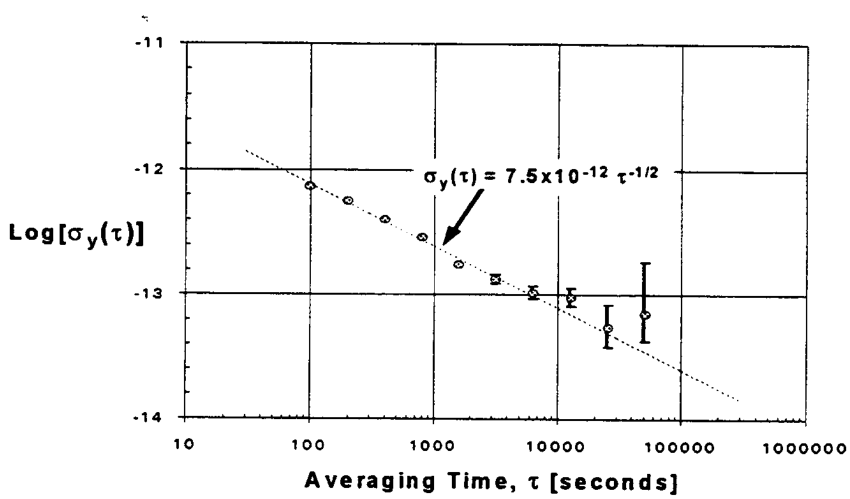

Figure 3. MRFS frequency stability during a period of extreme temperature stability. The dashed line results from a linear fit of the log-log plotted data for averaging time less than 4000 s. The slope of the resulting line is 0.50, consistent with white frequency noise.

While the MRFS under test was not specifically designed for vacuum operation, it was still of interest to ascertain how a commercial, off-the-shelf (COTS) MRFS would perform under spacelike conditions. The FEI design does have tapped screw holes in the main frame of the MRFS, allowing it to be bolted to the thermal control plate, ensuring good thermal conduction and preventing overheating. Figure 4 shows the performance of the MRFS in vacuum (squares) and in air (circles). In both cases, the temperature of the MRFS was stabilized by the thermal plate in the vacuum chamber. Again, the dashed curve in the figure corresponds to the desired performance for a SATCOM atomic clock. As the data clearly demonstrate, the performance of the COTS MRFS in vacuum is poor compared to its performance in air. As space missions, by definition, require operation in vacuum, the data of Figure 4 would preclude the use of this COTS MRFS in the SATCOM application. Moreover, while the smart MRFS concept improves the MRFS's performance in vacuum, it still does not meet the desired SATCOM level of performance. One explanation for the vacuum problem concerns the MRFS's thermal pathways. The data of Figure 2 clearly demonstrate the importance of temperature stability to Rb atomic clock operation. It should be noted, though, that the thermal pathways for the COTS MRFS were not designed for operation in space. In vacuum, the COTS MRFS's thermal pathways are altered, thereby creating a potentially greater sensitivity of the MRFS to thermal fluctuations. An alternate explanation for the vacuum problem postulates an influence of vacuum on the elastomers that hold the various physics package components in place. A change in the elastomer properties could cause a greater sensitivity of the MRFS to vibration. The vacuum-induced elastomer change could also shift the position of physics package components, thereby creating a greater sensitivity to microwave power or magnetic field fluctuations. Whatever the explanation for the vacuum problem, it is an issue of COTS MRFS device fabrication rather than device physics, and should not preclude the use of an appropriately modified MRFS in space. In fact, the space environment may be ideal for MRFS operation, as thermal control need be established only on the surface mounted the spacecraft.

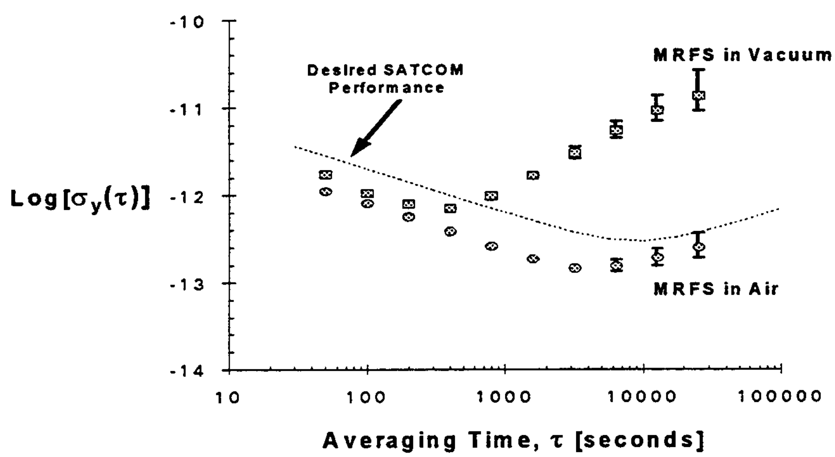

Figure 4. Experimental results of the Rb COTS clock's performance in terms of the Allan standard deviation. In the figure, squares represent operation in vacuum; circles represent operation in air. In both cases, the temperature of the clock was stabilized to +/-0.15°C by the thermal plate. Again, the dashed line corresponds to the desired SATCOM frequency stability and is only meant for reference purposes.

4. Conclusions

In conclusion, we have examined the timekeeping capability of an MRFS. We find that a very significant contributor to the random walk of frequency noise displayed by this standard is its sensitivity to ambient temperature. When the thermal environment is controlled, the unit displays extremely good frequency stability. Although the COTS nature of the MRFS precludes its direct use in the vacuum of space, the vacuum problem should be amenable to correction, as demonstrated by the fact that small (though not miniature) Rb clocks are already used in space systems. The results demonstrate that the timekeeping capability of MRFSs can meet space mission requirements by adequately controlling their ambient temperatures. While our testing was performed on a single MRFS design, we have no reason to believe similar levels of performance could not be obtained with other devices. The relationship between the statistical measure of MRFS frequency stability (i.e., the Allan standard deviation) and the level of ambient temperature fluctuations, suggests that a smart MRFS, employing microprocessor-based temperature compensation, could be fabricated and could have the potential to lessen temperature control requirements. Finally, the space environment might very well reduce the complexity of temperature control, as temperature isolation would only have to be actively maintained along the mounting surface of the MRFS.

References

1. T. J. Lynch and W. J. Riley, "Test Results for Prototype GPS Rubidium Clocks," in *Proceedings of the 15th Precise Time and Time Interval (PTTI) Applications and Planning Meeting*, pp.269-280, 1983.

2. W. J. Riley, "Rubidium Atomic Frequency Standards for GPS Block IIR," in *Proceedings of the 22nd Precise Time and Time Interval (PTTI) Applications and Planning Meeting*, pp. 221-230, 1990.

3. Frequency Electronics, Inc., Model FE-5650A Rubidium Atomic Frequency Standard specification sheet.

4. C. H. Volk and R. P. Frueholz, "The Role of Long-Term Lamp Fluctuations in the Random Walk of Frequency Behavior of the Rubidium Frequency Standard: A Case Study," *J. Appl. Phys.* **57**, 980-983 (1985).

5. D. A. Howe, D. W. Allan, and J. A. Barnes, "Properties of Signal Sources and Measurement Methods," in *Proceedings of the 35th Annual Symposium on Frequency Control*, pp. A13-A18, June 1981.

TECHNOLOGY OPERATIONS

The Aerospace Corporation functions as an "architect-engineer" for national security programs, specializing in advanced military space systems. The Corporation's Technology Operations supports the effective and timely development and operation of national security systems through scientific research and the application of advanced technology. Vital to the success of the Corporation is the technical staff's wide-ranging expertise and its ability to stay abreast of new technological developments and program support issues associated with rapidly evolving space systems. Contributing capabilities are provided by these individual Technology Centers:

Electronics Technology Center: Microelectronics, VLSI reliability, failure analysis, solid-state device physics, compound semiconductors, radiation effects, infrared and CCD detector devices, Micro-Electro-Mechanical Systems (MEMS), and data storage and display technologies; lasers and electro-optics, solid state laser design, micro-optics, optical communications, and fiber optic sensors; atomic frequency standards, applied laser spectroscopy, laser chemistry, atmospheric propagation and beam control, LIDAR/LADAR remote sensing; solar cell and array testing and evaluation, battery electrochemistry, battery testing and evaluation.

Mechanics and Materials Technology Center: Evaluation and characterization of new materials: metals, alloys, ceramics, polymers and composites; development and analysis of advanced materials processing and deposition techniques; nondestructive evaluation, component failure analysis and reliability; fracture mechanics and stress corrosion; analysis and evaluation of materials at cryogenic and elevated temperatures; launch vehicle fluid mechanics, heat transfer and flight dynamics; aerothermodynamics; chemical and electric propulsion; environmental chemistry; combustion processes; spacecraft structural mechanics, space environment effects on materials, hardening and vulnerability assessment; contamination, thermal and structural control; lubrication and surface phenomena; microengineering technology and microinstrument development.

Space and Environment Technology Center: Magnetospheric, auroral and cosmic ray physics, wave-particle interactions, magnetospheric plasma waves; atmospheric and ionospheric physics, density and composition of the upper atmosphere, remote sensing, hyperspectral imagery; solar physics, infrared astronomy, infrared signature analysis; effects of solar activity, magnetic storms and nuclear explosions on the earth's atmosphere, ionosphere and magnetosphere; effects of electromagnetic and particulate radiations on space systems; component testing, space instrumentation; environmental monitoring, trace detection; atmospheric chemical reactions, atmospheric optics, light scattering, state-specific chemical reactions and radiative signatures of missile plumes, and sensor out-of-field-of-view rejection.